

# Charge, Mass and Energy Distributions of Fission Fragments in $^{235}\text{U}$ and $^{239}\text{Pu}$ ( $n_{\text{th}}$ , f) Reactions

G.A. Abdullaeva, Yu.N. Koblik, V.P. Pikul, A.P. Morozov, A.F. Nebesny

100214, Institute of Nuclear Physics Uzbekistan Academy of Science

Ulugbek, Tashkent, Uzbekistan

koblik@inp.uz; gayanaabdullaeva@mail.ru

## Abstract

Heavy fission fragments distributions of  $^{235}\text{U}$  and  $^{239}\text{Pu}$  by thermal neutrons were measured using mass spectrometer. The treatment of the experimental data for the  $^{235}\text{U}(n_{\text{th}}, f)$  and  $^{239}\text{Pu}(n_{\text{th}}, f)$  nuclear fission reactions is presented. Charge, mass and energy yields of fission fragments with  $A_i = 125$  to  $157$ , kinetic energies from  $E_k = 45$  to  $E_k = 87$  MeV and effective ionic charges from  $z^* = 18$  to  $z^* = 30$  are obtained. The good consent of experimental and theoretical data for mass yields is indicated. Some increment in FF mass yields is observed for  $^{235}\text{U}(n_{\text{th}}, f)$  reaction in  $A = 151$ - $153$  mass range.

## Keywords

Mass Spectrometer;  $^{235}\text{U}$ ;  $^{239}\text{Pu}$ ; Fission Fragments (FF); Yields

## Introduction

It is well known that regarding the description of the nucleus properties at the nuclear fission, the agreement between experimental data and LDM (Liquid drop model) theory is not enough well for the actinide heavy nuclei due to the absence of accurate account of the contributions from the initial and final fission fragments shell structure. This phenomenon has been widely discussed in the literature, starting from the beginning of investigations in the field of the nuclear fission and it was shown that within the frame of LDM model, it was impossible to describe the asymmetry of nuclear fragments at the fission. Reasonable explanation was achieved by taking into account the shell structure of the initial nucleus and its fission fragments. The main difficulty to conduct such shell model calculations was connected with the absence of the single-particle calculations for the nuclear fission characterized by the enough large deformations with appearance of the neck structure at the fission and mean field potential.

In recent years, there has been great interest in fission yields. Fission yields are used in the calculation of

odd-even pairing effects, the number of prompt neutrons per fission of delayed neutron precursor yields and of delayed neutron spectra. Yields are used in the calculation of waste disposal inventories, and in the calculation of beta and gamma ray spectra of fission-product inventories; as well as in the calculation of decay heat, especially in the time from 1 to 1000 seconds after loss-of-coolant accident in a nuclear power plant. Such a calculation requires data for the independent yield of every fission product nuclide with a half-life longer than a few tenths of a second.

The experimental researches on mass, charges and energy distributions of fission fragments (FF) have revealed a number of features and laws in these distributions. Most of the experimental data are received by radiochemical methods which give the information about late stage of fission process but do not allow measuring kinetic energy and velocity of FF. Instrumental techniques (ionisation chamber, the semiconductor detectors, time of flight) velocity of FF, but have insufficient mass resolution (1.5-3 a.m.u.). Comparison of experimental data received by identical methods shows difference connected with insufficient accuracy of measurements and insufficient resolution of experimental techniques. The most precise and reliable results are obtained employing the deflection method of the FF in homogeneous consecutively located electric and magnetic fields. In recent time on the horizontal channels of some researches, reactors experiments have been carried out using deflection method of charged particles in magnetic and electric fields. There are "LOHENGRIN" mass spectrometer at the High Flux Reactor in Grenoble (France) and mass spectrometer in Tashkent (Institute of Nuclear Physics Uzbekistan Academy of Science - INP UzAS). Besides on the Grenoble reactor works the "Cosi-Fan-Tutte" spectrometer combined time of flight method,

ionization chamber and semi-conductor detectors. The experimental results obtained from "LOHENGRIN" mass spectrometer and "Cosi-Fan-Tutte" time of flight spectrometer and also from INP UzAS mass spectrometer have good agreement. These spectrometers define necessary energy and mass ranges of FF, identified with high accuracy FF mass numbers and determine their kinetic energies. Use of such experimental results permits to evaluate existing fission models and describes all stages of nuclei fission process by neutrons in more detail.

### Experimental Setup

FF yields measurements of  $^{235}\text{U}$  and  $^{239}\text{Pu}$  nuclei induced by thermal neutrons in heavy group are executed on electromagnetic mass spectrometer placed on the horizontal channel at nuclear reactor WWR-SM of INP UzAS. Mass spectrometer simultaneously separates FF by masses  $M$ , kinetic energies  $E_k$  and ionic charges  $z^*$ .

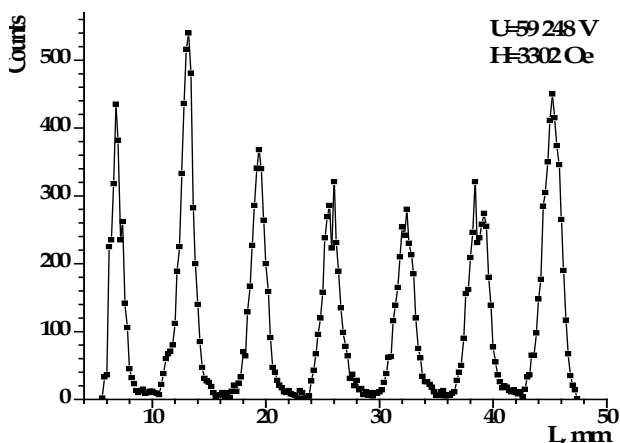


FIG. 1 PART OF SPECTRUM FROM THE SOLID DETECTOR

Thermal neutron flux on the target was  $\Phi_{th}=2 \times 10^{12}$  n/cm<sup>2</sup>·s and cadmium ratio  $-\Phi_{th}/\Phi=25$ . Targets with active layer in the sizes 40x5 mm<sup>2</sup> from  $^{235}\text{U}$  of 88% enrichment with thickness 150  $\mu\text{g}/\text{cm}^2$  and from  $^{239}\text{Pu}$  of 98% enrichment with thickness 100  $\mu\text{g}/\text{cm}^2$  were used in the measurements.  $^{235}\text{U}$  nuclei FF yield measurements for mass numbers  $A=125-155$ , kinetic energies  $E_k=42-78$  MeV and ionic charges  $z^*=18-29$  were carried out.  $^{239}\text{Pu}$  nuclei FF yield measurements for mass numbers  $A=125-157$ , kinetic energies  $E_k=45-87$  MeV and ionic charges  $z^*=18-30$  were also executed. For some ionic charges data interpolation was done. For FF detection, solid track detectors such as glass plates with sizes 50x60 mm<sup>2</sup> were used in the mass spectrometer focal plane. This detectors allowed simultaneously detecting several mass groups of FF. After irradiation plates looked through microscope, FF measurements with use of solid track detectors were

carried out for setup sets of electric field intensity ( $U$ ) and magnetic field intensity ( $H$ ). One of such spectra from solid track detector is presented in Fig.1

The focal plane of mass spectrometer calibration was done using  $\alpha$ -particles from spontaneous fission of  $^{252}\text{Cf}$  nuclei, and the next polynomial approximation (1) of experimental data was carried out to convert from linear sizes- $L$  (mm) of detector's plates to relative unites  $M/z^*$  (ion mass to charge ratio).

$$M/z^* = (4.51 + 4.5 \times 10^{-3}L + 1.9724 \times 10^{-6}L^2) \pm 5 \times 10^{-4} \quad (1)$$

FF distributions in focal plane of mass spectrometer are formed as linear spectra, where each peak is a superposition of FF with different values of masses and charges, but equal values of mass to charge ratios -  $M/z^*$  (within limits of mass spectrometer resolution).

Thus in region of the spectra impositions for mass definition in detected peak and for FF kinetic energies determination, electronic registration system was utilized. This system based on 32 Si-strips detector (64x64 mm<sup>2</sup>) was placed in the focal plane of mass spectrometer.

In Fig. 2, the energy spectrum of FF registered by one of the strips of Si-strip detector is shown where  $iY_z$  is FF yield, index  $i$  at the left corresponding to mass and  $z^*$  to ion charge. The bottom axis corresponds to channel numbers of the amplitude analyzer and top axis to channel energy in MeV.

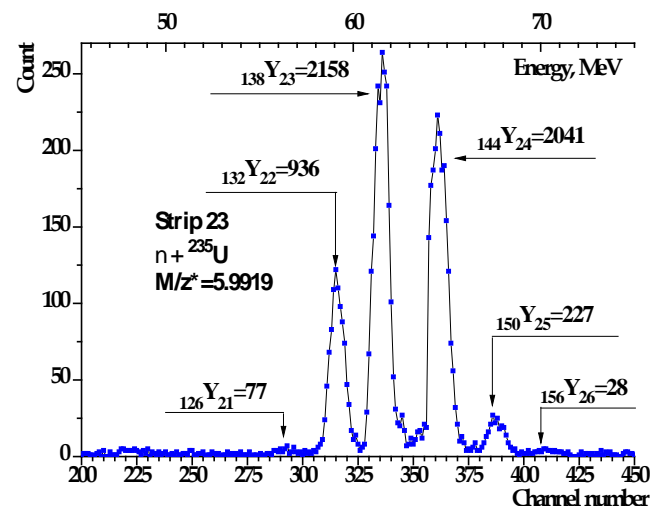


FIG. 2 THE ENERGY SPECTRUM FROM STRIP DETECTOR

### Results of Measurements

Measurement results of FF distributions from  $^{235}\text{U}(n_{th}, f)$  and  $^{239}\text{Pu}(n_{th}, f)$  reactions are shown in FIG. 3 and FIG.4 accordingly. In these figures the red points are experimental data and the blue curves are the experimental data treated by Gauss distribution.

### Charge Distributions of FF

The treatment of experimental spectra presented in FIG.3 and FIG.4 was executed by approximation for each peak with Gauss distribution. Fixation of peak center position ( $M/z^*$  coordinate) and events quantity in this peak area were realized according to expression (2):

$$y = y_0 + \frac{A}{\omega\sqrt{\pi/2}} \exp\left[-\frac{2(x-x_0)^2}{\omega^2}\right] \quad (2), \quad \omega = \frac{\sigma}{\sqrt{\ln 4}}$$

where  $y_0$  – background line,  $A$  – total area under the peak from background line,  $x_0$  – peak center,  $\sigma$  – peak width at half-height. It was supposed that total events amount in a peak is proportional to the yield from FF of ions which forms this peak. The obtained results for FF charge distributions are presented in TABLES 1 and 2 for  $^{235}\text{U}$  ( $n_{th}$ , f) and  $^{239}\text{Pu}$  ( $n_{th}$ , f) reactions, correspondingly.

### FF Mass Distributions

The further treatment included definition of FF yields

in conformity with their mass numbers. The mass yield for concrete value of heavy FF turned in the summation of all distributions on all its registered charge states. Received partial yields of FF  $y_i(z^*)$  were used for the calculation of a total yield of FF with mass  $A_i$ :

$$Y_i(A) = \sum_{z^*} y_i(z^*) \quad (3)$$

The results of FF mass distributions for  $^{235}\text{U}$  ( $n_{th}$ , f) and  $^{239}\text{Pu}$  ( $n_{th}$ , f) reactions are presented in FIG. 5 and FIG. 6. In FIG. 5 and 6, the curve 1 is our experimental results, 2– theoretical data and curve 3 on FIG.5 – experimental data for light hump of  $^{235}\text{U}$  ( $n_{th}$ , f) reaction FF. The good consent of experimental and theoretical data is observed. Some increment in FF mass yields is indicated for  $^{235}\text{U}$  ( $n_{th}$ , f) reaction in  $A = 151-153$  mass range. Results of measurements of FF relative yields of the light hump also show the presence of small increase in mass yield for  $A = 83$  that corresponds to FF in the heavy hump with  $A = 153$ .

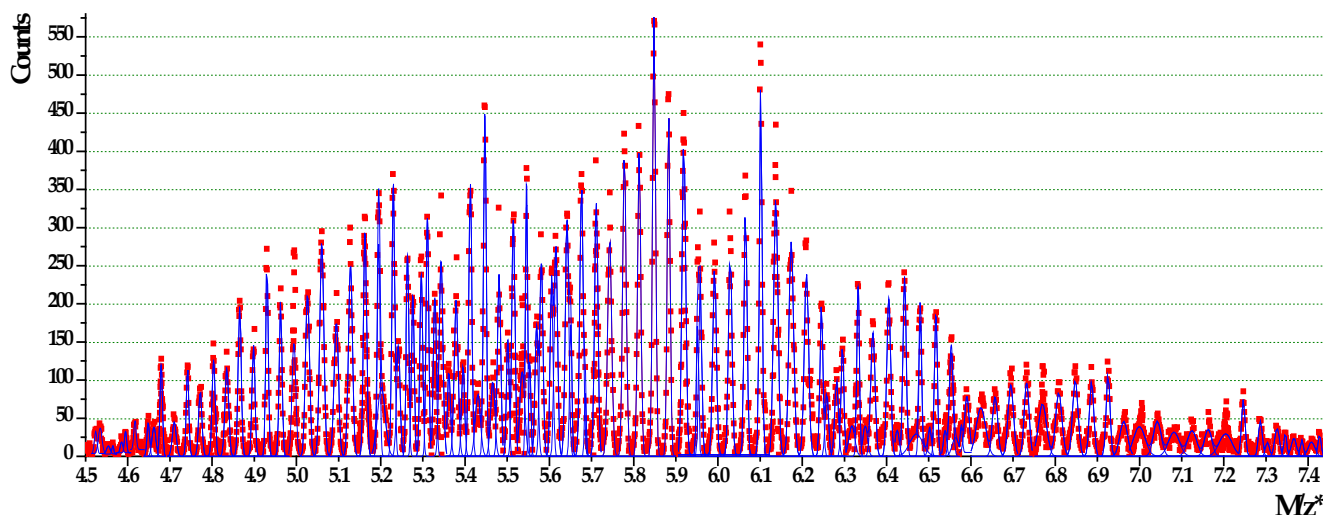


FIG. 3 FF DISTRIBUTION OF  $^{235}\text{U}$  ( $n_{th}$ , f) REACTION MEASURED BY MASS SPECTROMETER AT WWR-SM REACTOR

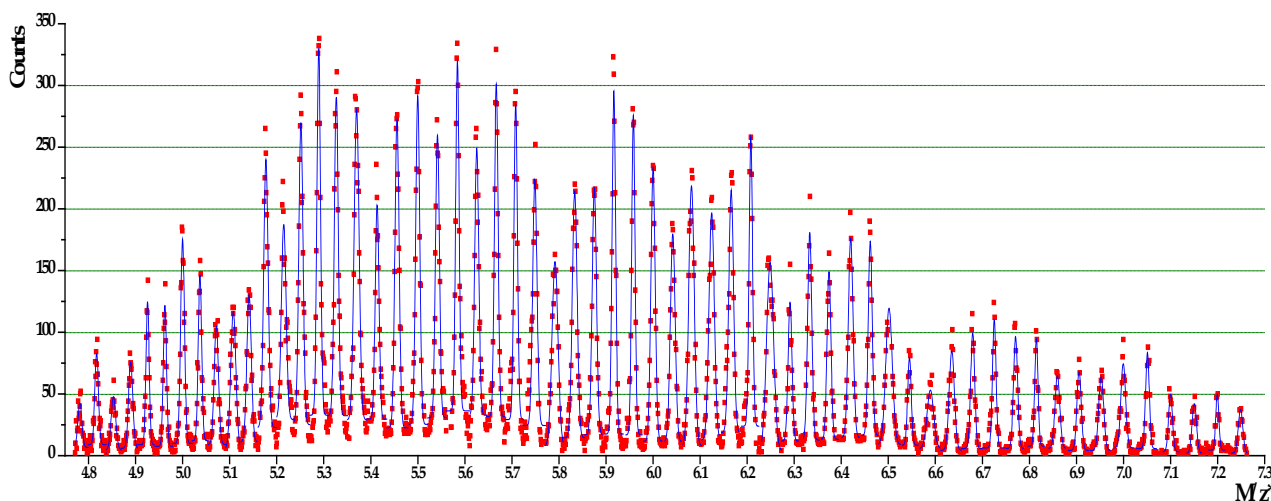
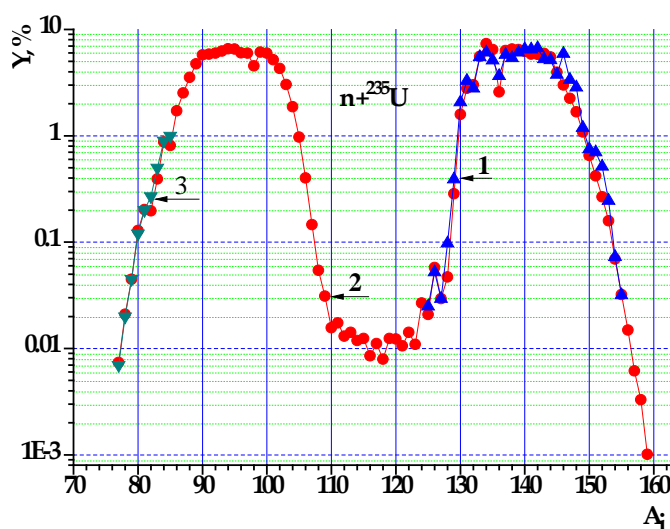
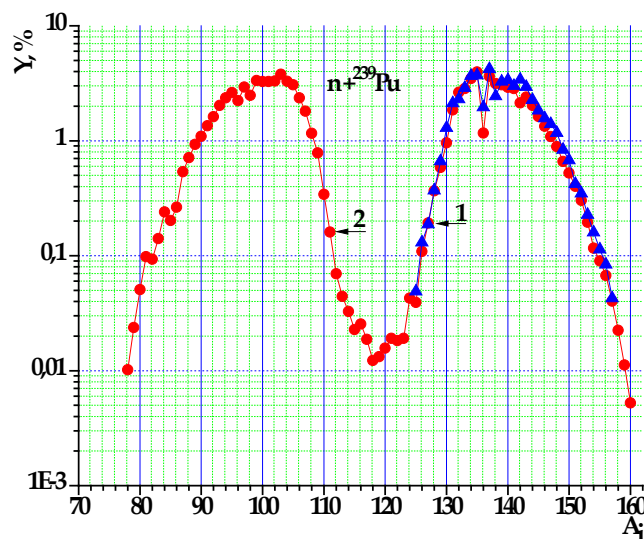


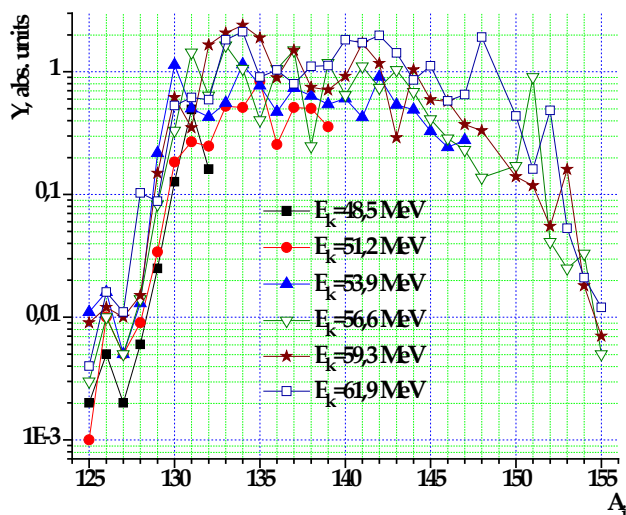
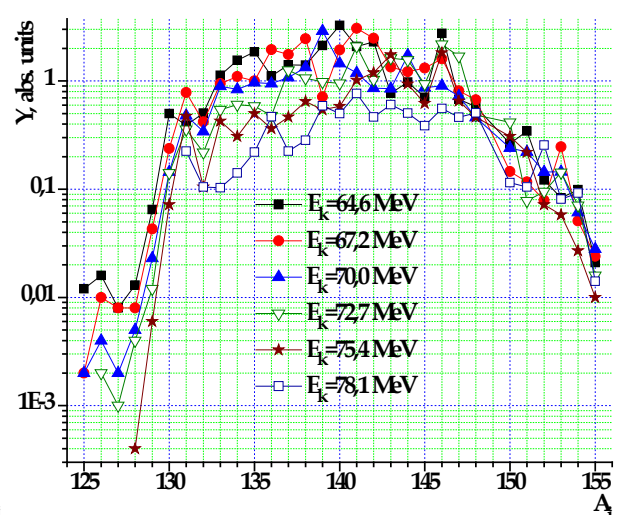
FIG. 4 FF DISTRIBUTION OF  $^{239}\text{Pu}$  ( $n_{th}$ , f) REACTION MEASURED BY MASS SPECTROMETER AT WWR-SM REACTOR

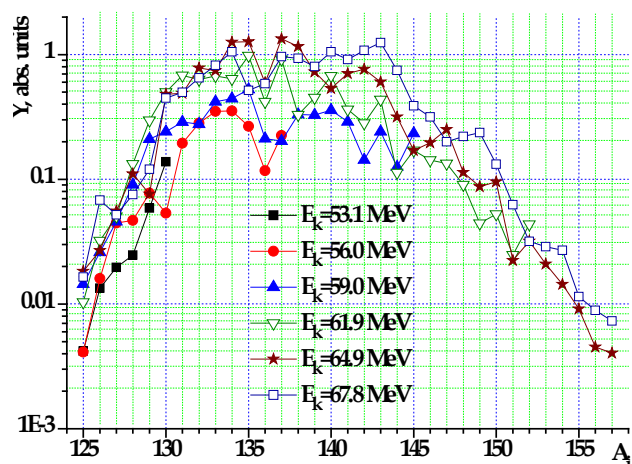
FIG. 5 FF MASS DISTRIBUTION OF  $^{235}\text{U}$  ( $n_{th}$ , f) REACTIONFIG. 6 FF MASS DISTRIBUTION OF  $^{239}\text{Pu}$  ( $n_{th}$ , f) REACTIONTABLE 1 CHARGE DISTRIBUTIONS OF HEAVY FF YIELDS FOR  $^{235}\text{U}$  ( $n_{th}$ , f) REACTION

$A_i$	$z^*=18$	$z^*=19$	$z^*=20$	$z^*=21$	$z^*=22$	$z^*=23$	$z^*=24$	$z^*=25$	$z^*=26$	$z^*=27$	$z^*=28$	$z^*=29$
125	0.002	0.001	0.011	0.003	0.009	0.004	0.012	0.002	0.002			
126	0.005	0.010	0.016	0.010	0.012	0.016	0.016	0.010	0.004	0.002		
127	0.002	0.005	0.005	0.005	0.010	0.011	0.008	0.008	0.002	0.001		
128	0.006	0.009	0.013	0.014	0.015	0.103	0.013	0.008	0.005	0.004	0.0004	
129	0.025	0.034	0.218	0.083	0.149	0.088	0.065	0.043	0.023	0.012	0.006	
130	0.127	0.184	1.140	0.332	0.618	0.530	0.499	0.238	0.144	0.141	0.072	
131	0.494	0.269	0.502	1.440	0.350	0.617	0.391	0.784	0.480	0.357	0.471	0.225
132	0.161	0.247	0.428	0.640	1.653	0.593	0.506	0.419	0.341	0.219	0.105	0.105
133		0.523	0.558	1.640	2.070	1.820	1.130	0.948	0.896	0.542	0.426	0.103
134		0.511	1.150	1.060	2.400	2.120	1.550	1.100	0.836	0.605	0.308	0.141
135		0.835	0.773	0.404	1.890	0.908	1.860	1.000	0.969	0.585	0.499	0.220
136		0.255	0.471	1.053	0.893	1.033	1.113	1.953	0.945	0.477	0.363	0.468
137		0.512	0.738	1.495	1.495	0.798	1.405	1.755	1.076	1.255	0.466	0.225
138		0.502	0.636	0.248	0.747	1.109	1.399	2.459	1.339	1.059	0.645	0.283
139		0.357	0.543	1.181	0.712	1.121	2.131	0.713	2.891	0.982	0.544	0.588
140			0.605	0.645	0.919	1.819	3.259	1.939	1.449	0.951	0.582	0.499
141			0.427	1.110	1.709	1.729	2.079	3.069	1.189	2.089	1.019	0.768
142			0.910	0.741	1.171	1.981	2.301	2.481	0.857	1.029	1.191	0.465
143			0.537	1.035	0.291	1.423	0.770	1.343	0.851	1.626	1.753	0.605
144			0.490	0.686	1.040	0.858	0.975	1.219	1.729	1.559	0.938	0.504
145			0.329	0.410	0.592	1.120	0.705	1.320	0.866	0.935	0.622	0.387
146			0.243	0.286	0.573	0.578	2.750	1.600	0.903	2.180	1.820	0.556
147			0.278	0.231	0.371	0.651	0.676	0.811	0.724	1.690	0.652	0.463
148				0.137	0.332	1.920	0.579	0.671	0.460	0.484	0.464	0.507
149				0.171	0.140	0.437	0.264	0.146	0.240	0.416	0.307	0.185
150				0.091	0.118	0.161	0.345	0.117	0.221	0.078	0.219	0.105
151				0.041	0.055	0.484	0.122	0.079	0.144	0.095	0.072	0.256
152				0.025	0.160	0.053	0.083	0.246	0.145	0.143	0.058	0.081
153				0.033	0.018	0.021	0.099	0.051	0.061	0.071	0.027	0.092
154				0.005	0.007	0.012	0.021	0.024	0.028	0.016	0.010	0.014
155				0.002	0.006	0.006	0.007	0.004	0.007	0.010	0.014	0.004

TABLE 2 CHARGE DISTRIBUTIONS OF HEAVY FF YIELDS FOR  $^{239}\text{Pu}$  ( $n_{\text{th}}$ , f) REACTION

$A_i$	$z^*=18$	$z^*=19$	$z^*=20$	$z^*=21$	$z^*=22$	$z^*=23$	$z^*=24$	$z^*=25$	$z^*=26$	$z^*=27$	$z^*=28$	$z^*=29$	$z^*=30$
125	0.004	0.004	0.014	0.010	0.018	0.016	0.013	0.007	0.002				
126	0.013	0.016	0.026	0.032	0.027	0.068	0.033	0.017	0.008				
127	0.020	0.045	0.046	0.051	0.056	0.052	0.042	0.021	0.016				
128	0.025	0.047	0.091	0.133	0.111	0.075	0.108	0.057	0.037				
129	0.059	0.077	0.210	0.297	0.076	0.120	0.209	0.084	0.059	0.031			
130	0.138	0.054	0.242	0.500	0.481	0.447	0.168	0.138	0.162	0.059			
131		0.194	0.289	0.682	0.489	0.499	0.777	0.559	0.292	0.135			
132		0.282	0.277	0.632	0.782	0.651	0.542	0.569	0.288	0.220			
133		0.350	0.419	0.674	0.745	0.820	0.765	0.833	0.438	0.287			
134		0.354	0.444	0.639	1.260	1.051	0.716	1.244	0.525	0.349	0.184		
135		0.267	0.526	0.981	1.270	0.517	1.091	0.695	0.568	0.668	0.245		
136		0.117	0.212	0.419	0.592	0.584	0.543	0.490	0.392	0.184	0.085		
137		0.225	0.203	0.916	1.342	0.962	0.983	0.748	1.884	0.396	0.304		
138			0.331	0.330	1.161	0.933	0.778	0.647	0.679	0.486	0.318		
139			0.328	0.452	0.728	0.804	0.886	1.458	0.900	0.463	0.308	0.162	
140			0.359	0.673	0.535	1.055	0.880	0.599	1.042	0.418	0.491	0.180	
141			0.290	0.364	0.705	0.912	0.372	0.784	0.499	0.957	0.450	0.208	
142			0.143	0.282	0.765	1.082	1.068	0.992	0.895	0.643	0.232	0.178	
143			0.241	0.437	0.604	1.250	0.634	0.648	0.493	0.517	0.370	0.242	
144			0.126	0.113	0.317	0.749	0.602	0.502	0.547	0.596	0.307	0.204	0.126
145			0.234	0.171	0.170	0.389	0.425	0.469	0.334	0.581	0.233	0.274	0.100
146				0.143	0.197	0.317	0.483	0.403	0.367	0.234	0.448	0.211	0.097
147				0.134	0.252	0.200	0.349	0.142	0.507	0.457	0.329	0.119	0.091
148				0.091	0.114	0.220	0.452	0.446	0.240	0.183	0.192	0.137	0.090
149				0.044	0.087	0.237	0.344	0.174	0.163	0.136	0.193	0.100	0.066
150				0.053	0.095	0.132	0.319	0.156	0.130	0.141	0.188	0.075	0.088
151				0.025	0.022	0.062	0.096	0.105	0.116	0.082	0.070	0.135	0.063
152				0.044	0.032	0.031	0.072	0.110	0.092	0.083	0.053	0.092	0.033
153					0.021	0.029	0.036	0.063	0.026	0.091	0.082	0.042	0.030
154					0.014	0.027	0.029	0.059	0.058	0.031	0.024	0.034	0.017
155					0.009	0.011	0.032	0.047	0.024	0.022	0.024	0.026	0.013
156					0.006	0.009	0.017	0.025	0.020	0.019	0.014	0.024	0.023
157					0.004	0.007	0.006	0.010	0.011	0.012	0.008	0.007	0.014

FIG. 7 FF ENERGY DISTRIBUTION OF  $^{235}\text{U}$  ( $n_{\text{th}}$ , f) REACTIONFIG. 8 FF ENERGY DISTRIBUTION OF  $^{235}\text{U}$  ( $n_{\text{th}}$ , f) REACTION

FIG. 9 FF ENERGY DISTRIBUTION OF  $^{239}\text{Pu}$  ( $n_{\text{th}}$ , f) REACTION

### Energy Distributions of FF

The kinetic energy distributions of  $^{235}\text{U}$  and  $^{239}\text{Pu}$  nuclei FF by thermal neutrons have been analysed by means of expression:

$$E_k = z^* e_0 \cdot \{1/[2\ln(r_1/r_2)]\} \cdot U = z^* \cdot k \cdot U, \text{ (MeV)}$$

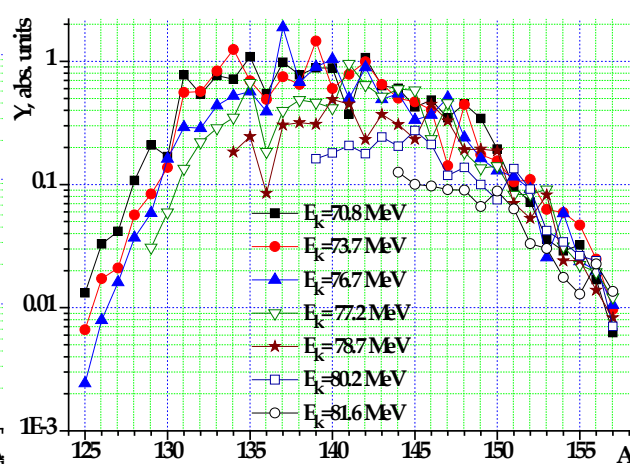
where  $z^*$  - the charge number of registered ion - FF,  $k = 1/[2\ln(r_1/r_2)] = (4.5963 \pm 0.0006) \times 10^{-5} \text{ MeV/e}_0$  - the geometrical parameter of mass spectrometer and  $U$  - the voltage on plates of electrostatical analyser, in V. The distributions of FF yields depending on kinetic energy for  $^{235}\text{U}$  ( $n_{\text{th}}$ , f) and  $^{239}\text{Pu}$  ( $n_{\text{th}}$ , f) reactions are presented in FIG. 7-10.

### Conclusions

Heavy FF distributions on ionic charges, masses and kinetic energy for  $^{235}\text{U}$  ( $n_{\text{th}}$ , f) and  $^{239}\text{Pu}$  ( $n_{\text{th}}$ , f) reactions are measured with use of mass spectrometer at WWR-SM nuclear reactor of INP UzAS. Measurements are executed in ranges of mass from  $A_i = 125$  to 157, kinetic energies from  $E_k = 45$  to  $E_k = 87 \text{ MeV}$  and effective ionic charges from  $z^* = 18$  to  $z^* = 30$ . From the results of measurements, the relative yields of fission fragments for  $^{235}\text{U}$  ( $n_{\text{th}}$ , f) and  $^{239}\text{Pu}$  ( $n_{\text{th}}$ , f) are defined depending upon mass number  $A$ . Heavy FF mass yields are in well accordance with the known reference theoretical estimations.

### ACKNOWLEDGMENT

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FIG.10 FF ENERGY DISTRIBUTION OF  $^{239}\text{Pu}$  ( $n_{\text{th}}$ , f) REACTION

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